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Visible Spectrum of Highly Charged Ions: the Forbidden Optical Lines of Kr, Xe, and Ba Ions in the Ar I to Ni I Isoelectronic Sequence

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Abstract

We present experimental data on visible lines produced by Kr (q=11+ to 22+), Xe (q=18+ to 35+), and Ba (q=28+ to 36+) ions, corresponding mainly to $3s^l$ $3p^m$ $3d^n$ configurations, obtained with the LLNL electron beam ion traps. Tentative assignments for the lines are made.

1. Introduction

Visible light emitted by highly charged ions (HCI) has potential applications in the diagnostics of tenuous plasmas and has been observed in interstellar plasmas (for forbidden lines from $2s^1$ $2p^m$ configurations see Ref.[1]). These lines are also seen in tokamak plasmas, in ions from ECR sources [2], and (for V-like and Ti-like ions) in electron beam ion traps (EBIT) [3,4,5]. These lines are mostly the result of intra--configuration transitions from a metastable level within the ground state configuration (open p or d subshells). If E1-transitions are forbidden, radiative deexcitation by magnetic dipole (M1) and higher order transitions ("forbidden transitions") take place, in some cases in the visible range. The line intensities are determined by the excitation processes, by cascades, and by competing non-radiative decay channels. Under low-density conditions, forbidden lines can appear as strong as E1-allowed transitions. Although experiments are likely to be more precise than atomic structure calculations, which for HCIs can have large error bars in relation to the energy of visible photons, they have to be guided by theoretical estimates. Reliable line identification ideally requires knowledge of the ion charge state. In an EBIT, an almost pure ion charge state for all but the heaviest elements can be selected by tuning the electron beam energy.

2. Experimental setup

Ions are produced and stored in an EBIT by an electron beam of variable energy axially compressed by a high magnetic field. They are visually accessible through apertures on the side. The trap is initially loaded with neutral atoms from an atomic beam. The ion charge state is mainly determined by the electron beam energy, but also influenced by charge-exchange processes.

The trap region was imaged using a cryogenically cooled, back-illuminated charge-coupled device (CCD) camera with an appropriate objective. The trap geometry, the cooling gas injection mechanism and the spatial distribution of charged states within the trap were studied. Two different light emitting regions appeared: (a) the trap region where the highly charged ions are stored, and (b) the short overlap of the electron beam with the cooling atomic beam, which crosses the central portion of the trap. The long delay (ms) between excitation and photon emission for forbidden transitions allows to image the spatial distribution of the ions, which in part extends outside the electron beam diameter. Earlier measurements with an X-ray slit camera had reflected only the electron beam overlap with the ion cloud, because of the short lifetimes of X-ray transitions. To obtain spectral information, a stigmatically imaging prism spectrograph was set up, which could cover the whole visible spectrum at once. The CCD camera used had a dark count rate of only a few counts/hour for each of the spectral lines being recorded. The spectra contained also spatial information about the ion distribution (see Fig. 1). This technique combining wide simultaneous spectral coverage, spatial resolution and large dynamic range was primarily developed for the observation of the ground state 1s hyperfine transitions of the H-like ions Ho^{66+} and Re^{74+} [6] in the visible range.

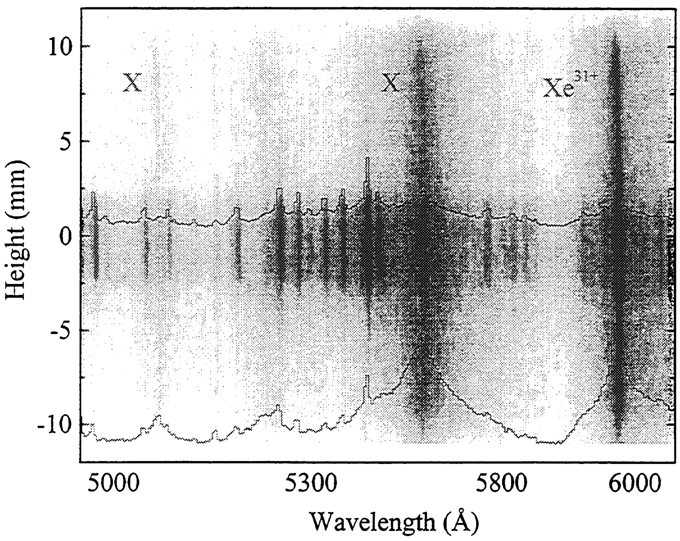

Fig. 1. Spectral image obtained from Xe at a beam energy of 2210 eV. Lineouts of the central spectrum and the outer spectrum are superimposed. An "X" marks unidentified transitions. Allowed transitions from XeI, XeII and XeIII appear mainly at the center region of the trap. In contrast, forbidden lines from trapped ions in contrast fill the whole trap height.

Table 1. Highly charged: Some of the forbidden lines observed in the visible range and tentative identifications.

Ion	Seq.	$I_p^{(q-1)+}$ (eV)	E_{beam} (eV)	$\lambda_{measured}$ (Å)	Int (a.u.)	Suggested identification	λ_{pred} (Å)	gA_{pred} (s^{-1})
Kr^{17+}	K I	588	615	**6369**	25	$3d^1\ ^2D_{5/2}$–$^2D_{3/2}$	6387	250
Kr^{18+}	Ar I	640	645	**4026.9**	30	$3p^53d^1\ ^3P_2$–$^3P_1$	4112	970
			715	**5793**	15	$3p^53d^1\ ^3F_2$–$^3F_3$	5660	500
Kr^{22+}	Si I	935	970	**3842.6**	100	$3p^2\ ^3P_2$–$^3P_1$	3845	700
Xe^{31+}	V I	1830	1890	**3962.3**	50	$3d^5\ ^4G_{9/2}$–$^4G_{7/2}$	3944	3110
			1870	5984	10	$3d^5\ ^4G_{9/2}$–$^4G_{11/2}$	6298	670
Xe^{32+}	Ti I	1920	1960	**4138.7**	120	$3d^4\ ^5D_3$–$^5D_2$	4052	3160
						$3d^4\ ^3H_6$–$^3H_5$	5991	580
Ba^{31+}	Mn I	1875	1900	4873	10	$3d^7\ ^4F_{5/2}$–$^2P_{3/2}$	4749	60
Ba^{32+}	Cr I	1964	1970	5681	4	$3d^6\ ^3D_2$–$^5F_3$	5578	830
Ba^{33+}	V I	2054	2170	5078	10	$3d^5\ ^4G_{9/2}$–$^4G_{11/2}$	5369	800
Ba^{34+}	Ti I	2146	2150	**3932**	30	$3d^4\ ^5D_3$–$^5D_2$	3932	3040

Ion: ionization stage; Seq.: isoelectronic sequence; $I_p^{(q-1)+}$: ionization energy or threshold for producing the ion; E_{beam}: beam energy threshold for the lines observed; $\lambda_{measured}$: measured wavelength; Int: observed relative intensities in arbitrary units; λ_{pred}: predicted wavelength; gA_{pred}: predicted product of the statistical weight $g = 2J+1$ and the transition rate A_{ik}. Strong lines with safe or confirmed identifications are displayed in bold.

3. Results

Table I is a compilation of the data acquired. The tentative identifications are done on the basis of calculations with the Cowan code [7]. Assignment of the proper charge state is aided by knowing the thresholds for appearance of the individual lines. For weak lines, the identifications are only tentative.

Kr spectra were taken at beam energies between 270 eV and 1670 eV, and ions from Kr^{11+} to Kr^{26+} were observed. The most prominent features of the spectrum are the K-like line at 6369 Å, the Ar-like lines at 4028 Å and 5793 Å, and the Si-like line at 3842 Å. The lines at 4028 Å and 3842 Å have been reported earlier [3], but only the second had been unambiguously identified. The two Ar-like lines at 4028 Å and 5793 Å are candidates for remote electron density diagnostic, since their intensity ratio can be expected to be sensitive in the range from 10^8 to 10^{10} e/cm^3.

For Xe, the beam energy was varied between 1670 eV and 2700 eV to study the ions from Xe^{29+} to Xe^{37+} (Mn-like to Cl-like). A very strong transition at 4363 Å is tentatively identified as the $^3P_2$-$^3P_1$ transition in the first excited configuration $3p^23p^53d^1$ of the Kr-like ion Xe^{18+}. In the V-like Xe^{31+}, a line appears at 5984 Å together with the line at 3963 Å observed by Morgan [3]. The Cowan code [7] predicts two possible decay channels for the $^4G_{9/2}$ level with an branching ratio of 1/5: a $^4G_{9/2}$-$^4G_{7/2}$ transition at 3944 Å and a $^4G_{9/2}$-$^4G_{11/2}$ transition at 6298 Å. We assume therefore that the 5984 Å line corresponds to the $^4G_{9/2}$-$^4G_{11/2}$ transition. For the lines registered at the Sc-like, K-like, Ar-like and Cl-like ionization stages, we do not have tentative identifications, in spite of many code runs to find candidate transitions.

For Ba, beam energies between 1670 eV and 2500 eV (Ba^{29+} to Ba^{36+}) were used. Five observed lines in the Ni, Co, and Fe sequences could not be assigned. Perhaps small Pt and Au impurities present in the trap during the Ba run could explain their presence. The line at 4873 Å could be the $^4F_{5/2}$-$^2P_{3/2}$ transition in the $3d^7$ configuration in Mn-like Ba^{31+}. Ba^{32+} shows a line at 5681 Å, probably the $^3D_2$-$^5F_3$ transition in the $3d^6$ configuration. In the V-like ion, we believe that the line at 5081 Å is the one predicted for the $3d^5$ configuration. The Ti-like Ba^{34+} shows the line at 3932 Å [3], as well as an unidentified line at 5002 Å.

4. Summary

We found some previously not observed lines in the spectrum of highly ionized Xe, Ba and Kr, and have made some tentative and some definitive identifications for them. We confirmed the three lines reported ealier by Morgan *et al.* [3] in the visible range. These data can help the study of stellar sources not accessible to X-ray observations and the diagnostics of other low density, highly ionized plasmas. The experimental wavelengths are sensitive tests for refined atomic structure codes. These results emphasize the need for dedicated, extensive calculations of the fine structure intervals of the ground state in all diagnostically relevant ions.

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